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WAVE FORCES ON ROUGH-WALLED CYLINDERS AT HIGH REYNOLDS NUMBERS

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ABSTRACT

This paper presents the results of an extensive experimental investigation of the in-line and transverse forces acting on sand-roughened circular cylinders placed in oscillatory flow at Reynolds numbers up to 1,500,000; Keulegan-Carpenter numbers up to 100; and relative roughnesses from 1/800 to 1/50. The drag and inertia coefficients have been determined through the use of the Fourier analysis and the least squares method. The transverse force (lift) has been analysed in terms of its maximum and root-mean-square values. In addition, the frequency of vortex shedding and the Strouhal number have been determined. The results have shown that all of the coefficients cited above are functions of the Reynolds number, Keulegan-Carpenter number, and the relative roughness height. The results have also shown that the effect of roughness is quite profound and that the drag coefficients obtained from tests in steady flow are not applicable to harmonic flows even when the fluid loading is predominantly drag.

INTRODUCTION

Of the scores of papers dealing with fluid loading on offshore structures none seems to have treated the effect of roughness on the force-transfer coefficients. Yet it is a fact that the structures in the marine environment become gradually covered with rigid as well as soft excrescences, (see Fig. 1). Thus, the fluid loading due to identical ambient flow conditions may be significantly different from that experienced when the structure was clean partly because of the 'roughness effect' of the excrescences on the flow and partly because of the increase of the 'effective diameter' of the elements of the structure.

In the absence of any data appropriate to the harmonic or wavy flows, it has been assumed that "the drag coefficients obtained from tests in steady flow" over artificially - or marine-roughened - cylinders "are applicable to wave flows at least when the loading is predominantly drag".[1] Even for large amplitudes of oscillations, there is only a finite vortex street comprised of vortices of nearly equal strength due to the 'nearly steady' nature of the flow. As the flow reverses, the situation is not that of a uniform flow (with or without free-stream turbulence) approaching a roughened cylinder but rather that of a finite vortex street approaching a rough-walled cylinder. Such a flow cannot be regarded identical to steady flow with some turbulence of fairly uniform intensity and scale as the present results show.

It is a well-known fact that organized, uniform roughness in steady flow about a cylinder precipitates the occurrence of the critical regime and gives rise to a minimum drag coefficient which is larger than that obtained with a smooth cylinder. This is partly because of the transition to turbulence of the free shear layers at relatively lower Reynolds numbers due to disturbances brought about by the roughness elements and partly because of the retardation of the boundary-layer flow by roughness (higher skin friction) and, hence, earlier separation.

In the supercritical and postcritical ranges of a steady flow over a roughened cylinder, the drag coefficient is considerably larger than that for a smooth cylinder primarily because of the larger wake which is brought about by the earlier separation due to the retardation of the boundary layer. Several facts are worth noting. Firstly, the postcritical drag coefficient depends on both the character of the flow and the surface condition of the cylinder. Secondly, the larger the effective roughness, the larger is the retardation of the boundary layer. This leads to earlier separation and larger drag coefficient. Thirdly, the pressure distribution about the cylinder is affected not only by the location of the separation point but also by the development of the retarded boundary layer ahead of separation. This in turn is affected not only by all the parameters characterizing the roughness but also by the character of the ambient flow. It is in fact partly for the difficulty of uniquely specifying the 'roughness' and partly for the differences in other test conditions that there are considerable differences between the data reported by various workers, particularly in the range of critical Reynolds numbers.[2] For example, the effective surface roughness may be larger or smaller than the nominal size

References and illustrations at end of paper.

of the roughness element depending on the shape and arrangement of the roughness elements. Evidently, the marine-grown roughness is unorganized and non-uniform. There are no simple means to classify such roughness. The possibility should be kept in mind that the consequences of unorganized roughness may be quite different from those of the organized roughness. This is primarily because of the fact that the unorganized roughness tends to reduce the spanwise coherence and hence the transverse force. It is apparent that much work remains to be done with marine-grown roughness before an approximate understanding of the effect of soft and rigid excrescences is achieved.

Attempts have been made[3] to experimentally determine an equivalent roughness through the use of uniform flow in a channel. An equivalent roughness determined in this manner may not necessarily give a meaningful measure of the effect of roughness as far as the boundary-layer flow over a circular cylinder is concerned. The purpose of this work is not to study this question but rather to show, among other things, that different types of roughness elements (marine roughness, sandpaper, polystyrene beads, sand, wire screens, etc.) can give rise to different drag-coefficient curves in the critical and postcritical ranges appropriate to the particular flow. It is in fact partly for this reason that it has been thought advisable to investigate afresh the effect of roughness on cylinders in harmonic flow using only sand of uniform size and packing rather than three different types of roughness.[4]

EXPERIMENTAL ARRANGEMENT

The oscillating flow system consisted of a large U-shaped vertical water tunnel with 3 ft by 3 ft test section. The cross-section of the two vertical legs is about twice that of the test section. The auxiliary components of the tunnel consisted of plumbing for hot and cold water, butterfly-valve system, and the air-supply system. Oscillations in the tunnel were obtained through the use of the butterfly valves (mounted on top of one of the legs of the tunnel) and a rack and pinion system actuated by an air-driven piston and a three-way control valve. The fluid oscillated smoothly with a period of $T = 5.507$ sec. The elevation, acceleration, and the in-line and transverse forces were monitored continuously by means of appropriate transducers. The analogue traces were absolutely free from secondary oscillations so that no filters were used between the outputs of the transducers and the recording equipment.

Circular cylinders with diameters ranging in size from 2 in. to 6.5 in. have been used. The cylinders were turned on a lathe from aluminum pipes or plexiglass rods. The length of each cylinder was such that it allowed 1/32 in. gap between the tunnel wall and each end of the cylinder. A doubleball precision bearing was inserted at each end of the cylinder in aluminum housings which sealed the cylinder air tight.

In view of the discussion concerning the one-parameter characterization of the roughness in terms of k/D, it was decided to use only one type of roughness element. The possible use of sandpaper, glass beads, wire screens, etc. was disregarded for they could have exhibited different packing and size-distribution characteristics. Clean sand was sieved through the use of standard sieves in order to obtain a given grain size. Then the test cylinder was covered with a thin layer of air-drying epoxy resin using a brush. When the epoxy coating reached a certain tackiness, the sand was sprinkled over the slowly rotating cylinder. Within about 10 minutes, the epoxy hardened and the cylinder was left alone for the epoxy to cure. This procedure has invariably resulted in cylinders of roughness with perfect uniformity, (see Fig. 2).

In order to determine the variation of the force coefficients with Reynolds number for a given Keulegan-Carpenter number and relative roughness, all cylinders were tested at the same relative roughness (k/D = 1/800, 1/400, 1/200, 1/100, and 1/50), and the experiments were carried out at three or four different temperatures.

Three transducers were used to generate three independent d.c. signals, each proportional to the instantaneous value of the elevation, velocity, and acceleration. In addition, the velocity at the test section was directly measured with a magnetic velocimeter. All four methods gave nearly identical results. These comparisons, as well as the perfectly sinusoidal and noise-free character of all acceleration and force traces speak for the suitability of the unique test facility used in this study. The additional details of the apparatus and procedure are described in Refs. 4, 5, and 6.

RESULTS AND DISCUSSION

The in-line force has been evaluated through the use of the Morison's equation and the drag and inertia coefficients C_d and C_m have been calculated through the use of the Fourier analysis and the method of least squares in a manner similar to that previously described in detail.[4-8] The lift or the transverse force coefficient C_L has been expressed in the usual manner by normalizing the amplitude of the first harmonic of the lift force by $0.5\rho L D U_m^2$. These coefficients may be shown, by dimensional analysis, to depend primarily on K, Re, and k/D where K is the Keulegan-Carpenter number defined as $U_m T/D$, Re is the Reynolds number defined by $U_m D/\nu$, and k/D is the relative roughness. Sand of uniform size and distribution, as used in the present investigation, forms a fairly organized roughness and additional parameters to describe size distribution and packing are not necessary. Thus, we have

$$[C_d, C_m, C_L, \ldots] = f_i(K, Re, k/D) \quad (1)$$

It appears, for the purposes of Eq. (1), that the Reynolds number is not the most suitable parameter involving viscosity. The primary reason for this is that U_m appears in both K and Re. Thus, replacing Re by $\beta = Re/K = D^2/\nu T$ in Eq. (1), one has

$$C_i \text{ [a coefficient]} = f_i(K, \beta, k/D) \quad (2)$$

in which $\beta = D^2/\nu T$ is called by this writer the 'frequency parameter'.[4-6]

From the standpoint of dimensional analysis, either the Reynolds number or β could be used as an independent parameter. Evidently, β is constant for a series of experiments conducted with a cylinder of diameter D in water of uniform and constant temperature T. Then the variation of the force coefficients with K may be plotted for constant values of β. Subsequently, one can easily recover the Reynolds number from Re = βK and connect the points, on each β = constant curve, representing a given Reynolds number.

From the standpoint of the laminar boundary-layer theory, β represents the ratio of the rate of diffusion of vorticity through a distance δ (the boundary-layer thickness) to the rate of diffusion through a distance D. This ratio is also equal to $(D/\delta)^2$ and, when it is large, gradients of velocity in the direction of flow are small compared with the gradients normal to the boundary, a situation to which the boundary-layer theory is applicable.

In view of the fact that each coefficient depends on at least three independent parameters (Re, K, and k/D), it is not possible to show on two-dimensional plots the variation of either C_d or C_m for all values of Re, K, and k/D. However, this difficulty is alleviated by the fact that the variation of a given force coefficient for a given Re and k/D is not very strong from one K to another. Thus, it has been decided to choose five representative K values, namely K = 20, 30, 40, 60, and 100, to present the variation of C_d and C_m with Re for various values of k/D.

Figures 3 through 12 show C_d and C_m for five values of K as a function of the Reynolds number. Each curve on each plot corresponds to a particular relative roughness. Also shown on each figure is the corresponding drag and inertia coefficient for the smooth cylinder at the corresponding K value.

The k/D = constant curves on each plot are quite similar to those found for steady flow about rough cylinders.[9-12] For a given relative roughness, the drag coefficient does not significantly differ from its smooth cylinder value at very low Reynolds numbers. As the Reynolds number increases, C_d for the rough cylinder decreases rapidly, goes through the drag crisis in the critical region at a Reynolds number considerably lower than that for the smooth cylinder and then rises sharply to a nearly constant postcritical value. The larger the relative roughness the larger is the magnitude of the minimum C_d and the smaller is the Reynolds number at which that minimum occurs. However, there appears to be a minimum Reynolds number below which the results for roughened cylinders do not significantly differ from those corresponding to smooth cylinders. In other words, The Reynolds number must be sufficiently high for the roughness to play a role on the drag and flow characteristics of the cylinder.

The figures for the drag coefficient also exhibit a few other important features. First, even a relative roughness as small as 1/800 can give rise to postcritical drag coefficients which are considerably larger than those for the smooth cylinder. Secondly, the asymptotic values of the drag coefficient for roughened cylinders, within the range of Reynolds and Keulegan-Carpenter numbers encountered, can reach values which are considerably higher than those obtained with steady flows over cylinders of similar roughness. In other words, it is not safe to assume that the drag coefficient for roughened circular cylinders in harmonic flow will, following the drag crisis, asymptotically reach from under a postcritical value (for all K values) identical to that for steady flow over similar cylinders. Evidently, such a conjecture is not accurate even for K values as large as 100 (corresponding to a wave-height-to-diameter ratio of about 30). It is therefore important to remember that the effect of roughness depends not only on the relative size of the roughness elements but also on the characteristics of the ambient flow.

Intuitively, one may argue that the postcritical drag coefficient for harmonic flow over a cylinder of given roughness must, for sufficiently large values of K and Re, approach that for steady flow over the same cylinder and that either the relative magnitude of acceleration or the ratio of the maximums of the inertial force to drag force must serve as a measure of the degree of unsteadiness of the flow. In fact, the comparison of the smooth cylinder data for the two flows lends some credence to this argument. However, the fact that this argument does not hold true for roughened cylinders and that the effect of roughness is considerably more complex may be demonstrated with the following example. Consider a smooth and a rough cylinder in a flow for which K = 100 and Re = 1,000,000. For the smooth cylinder case, one has: C_{ds} = 0.65 and C_{ms} = 1.75. For the rough cylinder case (assuming k/D = 1/100), one has: C_{dr} = 1.55 and C_{mr} = 1.60. Then the acceleration modulus defined by $M = D(dU/dt)_{max}/U_m^2 = 2\pi/K$ and the ratio of the maximum inertial force to maximum drag force given by $R = (\pi^2/K)(C_m/C_d)$ become M_s = 0.063, R_s = 0.27 and M_r = 0.063 and R_r = 0.10, respectively, for the smooth and rough cylinder cases. Evidently, a value of 0.27 for R_s (for the example under consideration) is small enough for the harmonic flow to behave as a pseudo-steady flow over a smooth cylinder. However, a value of 0.10 for R_r is not small enough for a rough cylinder in harmonic flow for the postcritical drag coefficient to reduce to that for steady flow over a cylinder of identical roughness. Apparently, the physical mechanisms responsible for the large effect of roughness in the range of K and Re values encountered are considerably more complex than those suggested by a simple minded argument. A plot of the variation of C_d with K for a given k/D and Re (say Re = 1,000,000) shows that C_d first rises and then gradually decreases. The rate of this decrease is such that K will have to be several times larger than the largest value encountered herein for C_d to finally reduce to that for a steady flow over a cylinder of identical roughness. It appears that the effect of roughness and the vortices shed in the previous parts of a cycle on the separation points is not similar to the effect of roughness alone on steady flow about a cylinder. A simple sketch of the flow pattern (see Fig. 13) points out some of the important differences between steady and harmonic flows about circular cylinders and acts as a warning against simple minded explanations of the observed variations in the force coefficients.

The Reynolds number at which the drag crisis occurs gives rise to a steep rise in C_m. In other words, for a given relative roughness, C_m rises rapidly to a maximum at a Reynolds number which corresponds to that at which C_d drops to a minimum. At relatively higher Reynolds numbers, C_m decreases somewhat and then attains nearly constant values which are lower than those corresponding to the smooth cylinders. It is also apparent from the inertia-coefficient curves that the smaller the relative roughness the larger is the maximum inertia coefficient. For relatively smaller roughnesses, such as k/D = 1/800, the terminal value of C_m is nearly equal to that of a smooth cylinder. The behaviour of C_m is not entirely unexpected. It has long been noted that whenever there is a rise in the drag coefficient, there also is a decrease in the inertia coefficient. This is also evident from the entire smooth-cylinder data shown in Figs. 3 through 12 together with those corresponding to the rough cylinders.

Before closing the discussion of the drag and inertia coefficients, it is necessary to point out the remarkably consistent behaviour of the data points. Perhaps it would not have been too surprising had the data been taken for one relative roughness through the use of only one cylinder. In the present investigation, the use of several cylinders and several temperatures for a given cylinder always provided data for nearly identical k/D, Re, and K values. For instance, the C_d and C_m values obtained at a given K, Re, and relative roughness k/D, using a 5 in. cylinder at a low temperature correspond to the C_d and C_m values using a 4 in. cylinder at a high temperature. Remembering the fact that not only the actual size of the cylinders but also the size of the sand grains differed in order to obtain the same k/D, and the fact that the experiments were carried out at different temperatures and times, one fully realizes that the correlation of the data and the relatively small scatter are indeed quite remarkable. This is due not only to the repeatibility of the tests but also due to the vibration-free operation of the entire tunnel system.

The correlation length along the cylinders was not directly measured. However, one series of experiments was conducted with a 2.18-diameters (12 in.) long, centrally located, section of a 5.5 in. size cylinder which 'floated' on the ends of the force transducers with small gaps (1/64 in.) between the section and the rest of the rigidly supported 12 in. long sections. The floating and the dummy sections were coated with sand for a relative roughness of k/D = 1/100, following a series of tests with the initially smooth sections. The comparison of the lift, drag, and inertia coefficients obtained with the short section with those obtained with the longer section spanning the entire test section has shown that the corresponding sets of coefficients are nearly identical. Evidently, the force-cancelling effects of phase shifts which may have been brought about by three-dimensional effects were either insignificant or non-existent. Thus, it is concluded that both the three-dimensionality effects and the boundary-layer effects played very little or no role in the present experiments. However, a comparison of the results shown in Figs. 3 through 12 with the previously reported preliminary results for K = 50 alone indicates[4,5] the effect, particularly in the critical region, of the type of roughness element used on the variation of the force-transfer coefficients with the Reynolds number. Previously, sand, sandpaper, and polystyrene beads were used as roughness elements for a given cylinder in order to achieve the desired roughness in a given Reynolds number range. A detailed study of the effective roughness of each type of roughness element and the discussions with the manufacturer have shown that the effective roughness of the sandpaper is larger than the height of the mean sand particles applied on it. Furthermore, the gluing of the sandpaper on the cylinder invariably resulted in a 'joint' along the cylinder which might have generated larger disturbances and promoted earlier transition. The polystyrene beads, on the other hand, present an effective-roughness height which is often smaller than their actual size.[3] In spite of these differences in the 'effective roughness' of the various types of roughness elements, however, the terminal values of the drag coefficients in the postcritical region remained practically unchanged for a given actual effective relative roughness whether the data were obtained with sand alone or with a combination of other roughness elements. Evidently, it will be most interesting and desirable to carry out similar experiments with cylinders roughened in the ocean environment. As pointed out earlier, marine-grown roughness is unorganized and is comprised of both rigid and soft excrescences. The testing of such cylinders in steady uniform flow[1] is not sufficient for the purposes under consideration, namely the determination of the fluid loading on offshore structures.

The data given in Figs. 11 and 12 are replotted in Fig. 14 as a function of the roughness Reynolds number defined by $Re_k = U_m k/\nu$ for all values of k/D. Similar plots may be prepared for other values of K through the use of Figs. 3 through 10.

It is rather remarkable that C_d and C_m become practically independent of k/D for Re_k larger than about 300. In other words, for sufficiently large values of the roughness Reynolds number, the drag and inertia coefficients for a roughened cylinder in a given harmonic flow are determined by the height of the excrescences rather than by the diameter of the cylinder. The importance and the consequences of this result are self evident for postcritical Reynolds number simulation for flow over circular cylinders. A detailed discussion of this and other pertinent concepts for steady flow over roughened cylinders is presented by Szechenyi[11] and will not be repeated here.

The transverse force coefficients for smooth cylinders have previously been discussed in Refs. 4, 5, and 6. Suffice it to note that for smooth cylinders C_L depends on Re and decreases rapidly to a value of about 0.25 as Re increases.

The results for the roughened cylinders are presented in Fig. 15 as a function of K for various values of the 'frequency parameter' and one particular value of k/D. Additional details and data may be found in Ref. 13. Evidently, C_L does not vary appreciably with either the Reynolds number or the frequency parameter. The data presented in Ref. 13 for other values of k/D show that C_L does not vary with k/D also within the range of the parameters encountered. If there is some variation with these parameters (β or Re), it is certainly masked by the scatter in the data. The transverse force coefficient inevitably exhibits a larger scatter than that for the in-line force coefficients because of the somewhat random nature of the shedding of vortices. In fact, it is not too uncommon to obtain a variation of 20 to 25% for a given K value. This fact is of importance in discussing the effect of the Reynolds number on the lift coefficient.

Also shown in Fig. 15 is the lift coefficient for smooth cylinders for β values in the range of 1,000 to 2,000. It is rather surprising that the smooth cylinder data at relatively low values of β (lower Reynolds numbers) form more or less the upper limit of the rough cylinder data. In other words, the lift coefficient for rough cylinders does not depend on Re and become almost identical with those for smooth cylinders at very low Reynolds numbers. This behaviour of the lift coefficient for rough cylinders is in conformity with the experimental fact that the postcritical drag coefficient for rough cylinders (steady or unsteady) nearly returns to its subcritical value (se Figs. 3 through 12). The implied dynamic similarity between the two flow situations will have to be explored in greater detail.

The alternating nature of the transverse force is as important as its magnitude. It is for this reason that the frequency of the alternating force has also been calculated. The results have shown that the Strouhal number defined by $St = f_v D/U_m = f_r/K$ remains fairly constant at a value of about 0.22 for all roughnesses, relative amplitudes, and Reynolds numbers larger than about 20,000. In the case of smooth cylinders, however, f_r and hence St varies somewhat with Re and K. Higher harmonics of the lift force and vortex shedding frequency have not been examined in great detail and will not be discussed herein.

PRESENT DATA AND THE WAVE INDUCED LOADS

In considering the relevance of the coefficients presented herein and of the equation devised by Morison to wave induced loads on offshore structures, it is of course important to take into account the differences between uniform two-dimensional harmonic flow and the wave motion where the velocity vector both rotates with time at a point and decays in magnitude with depth. Furthermore, one should take note of the fact that the roughness used in this investigation is quite uniform and organized whereas the marine-grown roughness is non-uniform, unorganized, and comprised of both rigid and soft excrescences. The spanwise variation of the flow in general lead to reduced spanwise coherence. It is safe to assume that both the three-dimensionality of the flow and the reduced correlation along the cylinder, in an ocean environment, tend to increase the base pressure and thus give rise to postcritical drag coefficients which are smaller than those obtained with purely two-dimensional flows. The drag coefficients presented herein obviously represent their maximum possible values since they have resulted from a uniform, two-dimensional flow where the instantaneous wake of the cylinder has the highest possible degree of spanwise coherence. Thus, the approximate equality of the reduced drag coefficient due to reduced spanwise coherence in wavy flows to the drag coefficient in steady uniform flows, where a high degree of spanwise coherence is maintained, is rather fortuitous and does not certainly imply the equality of the two drag coefficients in the drag dominated region of the K values. In fact, the comparison of a drag coefficient resulting from a relatively poor spanwise coherence with that resulting from a nearly perfect coherence is not justified. It is rather unfortunate that even the experiments with wavy flows cannot be expected to isolate the effect of reduced spanwise coherence since such experiments surely bring in other factors (e.g. the ratio of the vertical to horizontal component of wave velocity, shear, etc.) whose influence is combined in a complex way with that of the reduced correlation.

CONCLUSIONS

1. The drag and inertia coefficients for roughened cylinders depend on Re, K, and k/D.

2. The drag coefficient first undergoes a drag crisis, depending on the relative roughness, and then rises to an asymptotic value within the range of Reynolds numbers tested. The asymptotic values of the postcritical drag coefficient are larger than those corresponding to the steady flow over cylinders of similar roughness. Furthermore, the larger the relative roughness the larger is the asymptotic value of the drag coefficient.

3. It is not safe to assume that the drag coefficient for roughened cylinders in harmonic flow will, following the drag crisis, asymptotically reach, from under, a postcritical value identical to that for steady flow over similar cylinders, independent of the magnitude the Keulegan-Carpenter number.

4. The similarity between the drag coefficients obtained from the field tests and those obtained with steady uniform flow over similar cylinders under controlled laboratory conditions is rather fortuitous and is a consequence of the reduced spanwise coherence in the ocean tests.

5. The inertia coefficient also undergoes a rapid change at Reynolds numbers corresponding to the drag crisis in the critical region. The maximum as well as the asymptotic value of C_m depends, as in the case of C_d, on K and k/D.

6. Within the range of parameters tested, the lift coefficient for rough cylinders does not depend on Re. Its distribution is, surprisingly enough, very close to that obtained with smooth cylinders at very low Reynolds numbers. The Strouhal number for roughened cylinders remains nearly constant for all Reynolds numbers, larger than about 20,000, at about 0.22.

7. The results reported herein and the conclusions arrived at are applicable only to cylinders in harmonic flow with zero mean velocity. The force coefficients for wavy flows may differ somewhat from those presented herein partly due to the reduced spanwise coherence, partly due to the three-dimensionality of the flow, and partly due to the nonlinear interaction of the currents with waves. It should also be remembered that the marine-grown roughness may differ significantly from the organized sand roughness used in the tests reported herein.

NOMENCLATURE

C_d	drag coefficient through the Fourier analysis
C_L	lift coefficient
C_m	inertia coefficient through the Fourier analysis
D	diameter of the cylinder
f_r	relative frequency, $f_v T$
f_v	frequency of the transverse force
K	Keulegan-Carpenter number
k	roughness height, k/D = relative roughness
L	length of the cylinder
Re	Reynolds number, $U_m D/\nu$
Re_k	roughness Reynolds number, $U_m k/\nu$
St	Strouhal number = $f_v D/U_m = f_r/K$
T	period of oscillations
U_m	maximum velocity in a cycle, $U = -U_m \cos 2\pi t/T$

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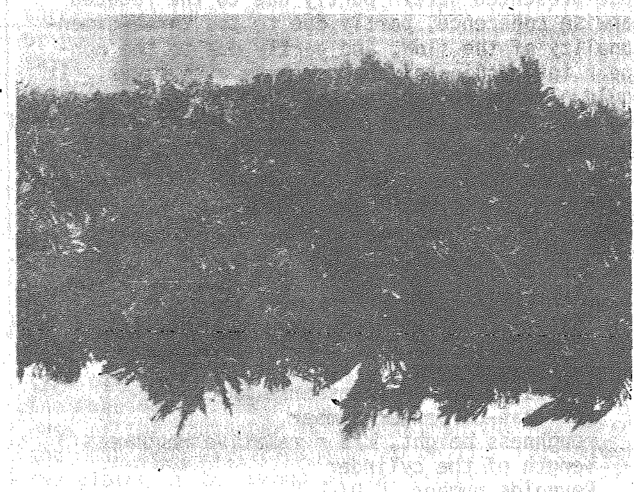

Fig. 1 - Sample marine-grown roughness (courtesy of Mr. Dallas Meggitt.)

Fig. 2 - Sample sand roughness (k = 0.018 inches, magnified 20 times).

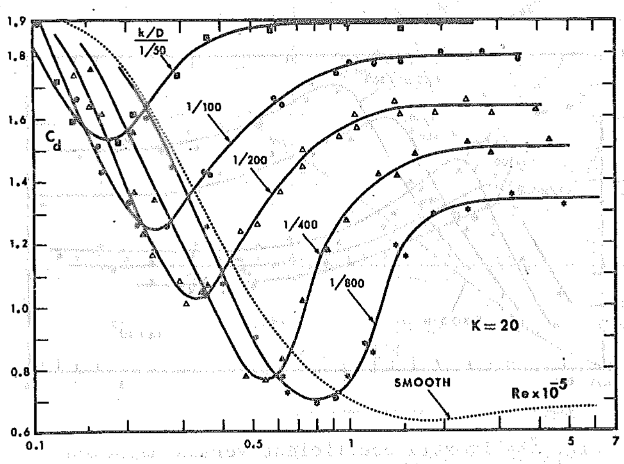

Fig. 3 - Drag coefficient versus Reynolds number for K = 20.

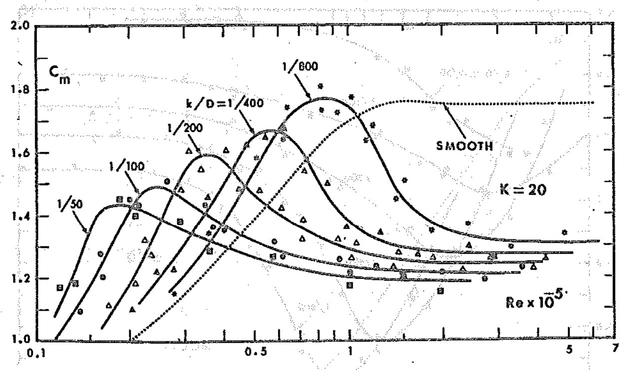

Fig. 4 - Inertia coefficient versus Reynolds number for K = 20.

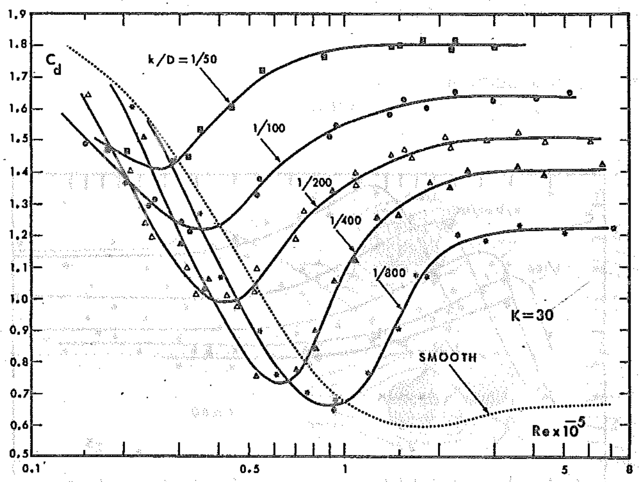

Fig. 5 - Drag coefficient versus Reynolds number for k = 30.

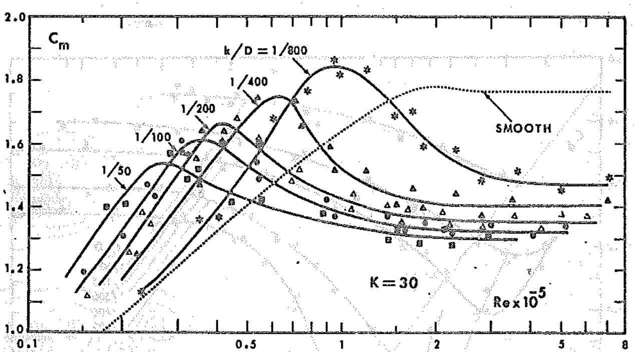

Fig. 6 - Inertia coefficient versus Reynolds number for K = 30.

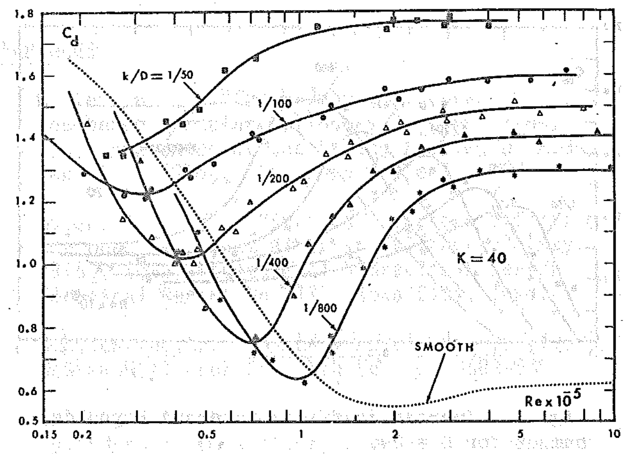

Fig. 7 - Drag coefficient versus Reynolds number for K = 40.

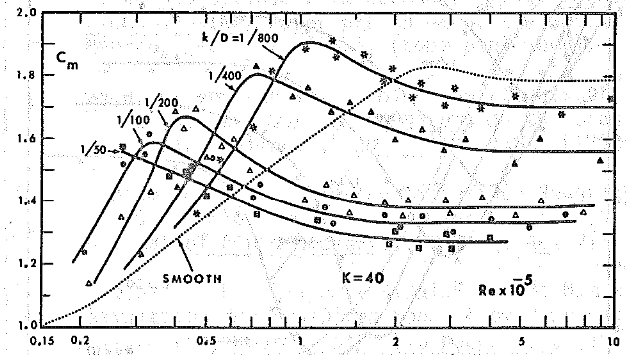

Fig. 8 - Inertia coefficient versus Reynolds number for K = 40.

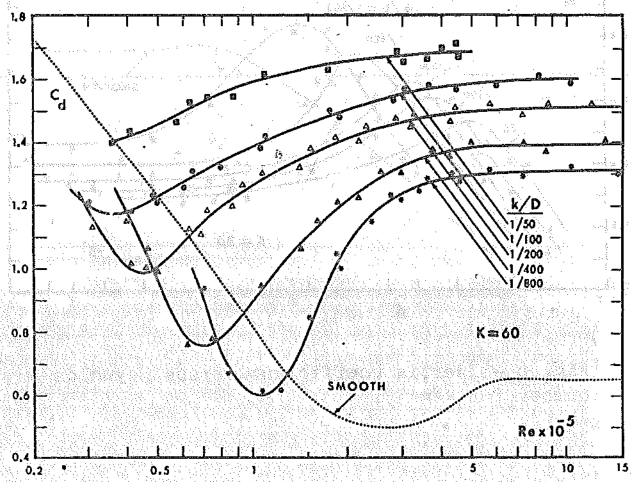

Fig. 9 - Drag coefficient versus Reynolds number for K = 60.

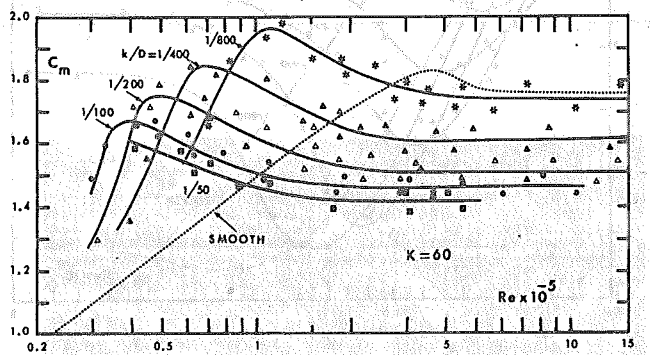

Fig. 10 - Inertia coefficient versus Reynolds number for K = 60.

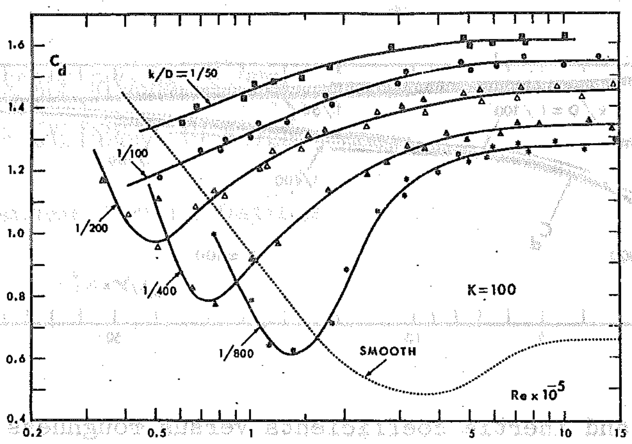

Fig. 11 - Drag coefficient versus Reynolds number for K = 100.

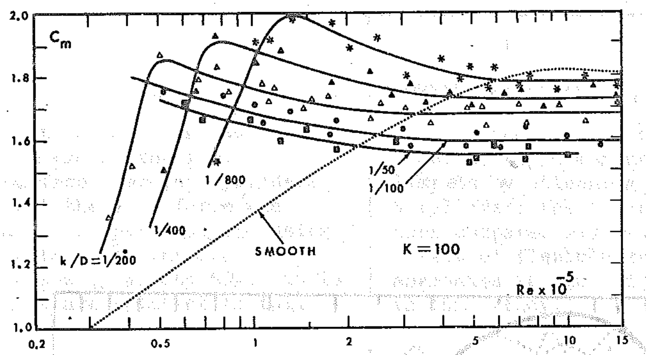

Fig. 12 - Inertia coefficient versus Reynolds number for K = 100.

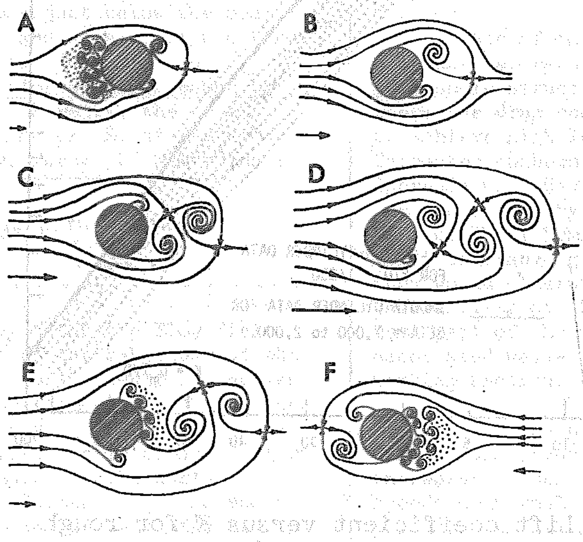

Fig. 13 - Flow pattern in harmonic flow.

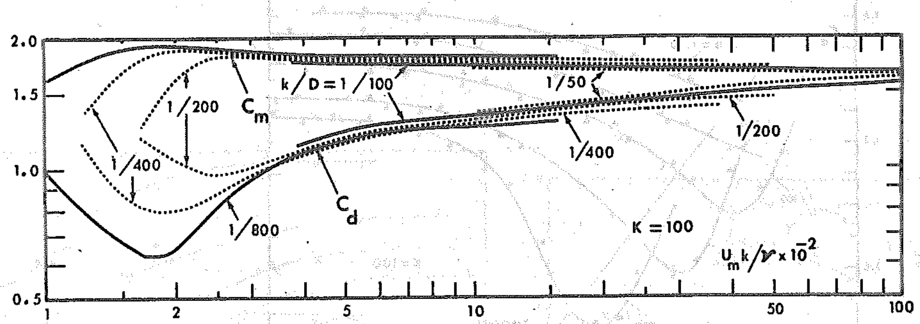

Fig. 14 - Drag and inertia coefficients versus roughness Reynolds number.

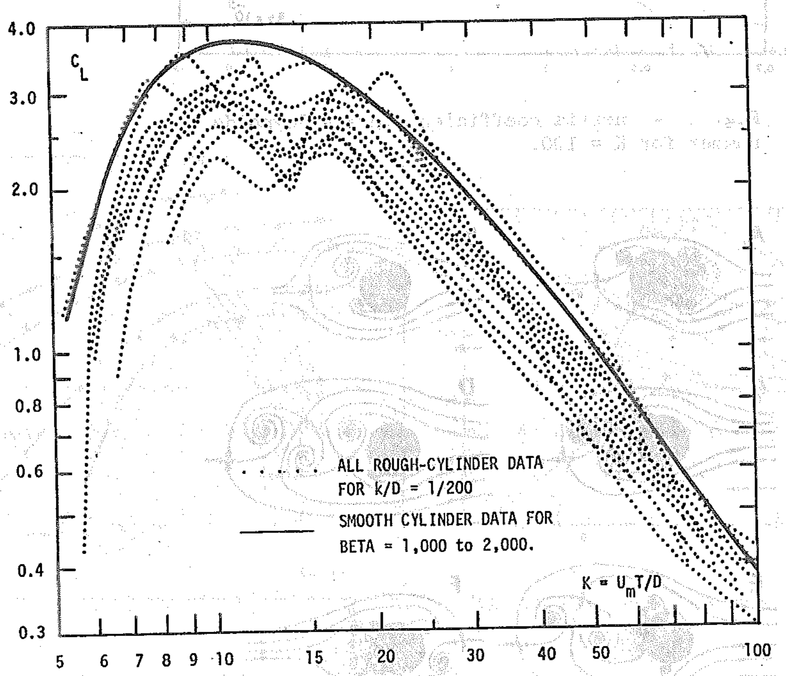

Fig. 15 - Lift coefficient versus K for rough cylinder.